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Wave Flow of Liquid Films

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The main goal of the book is generalization of the existing knowledges of the wavy flow of falling thin liquid films and transfer processes in wave regimes. The methods of local measurements of hydrodynamic parameters have been analyzed. The theoretical models of wave motion taking into account non-linearity, non-stationarity, dispersion, multi-wave character and other effects have been stated. The waves of different types, including solitons, have been described theoretically and experimentally. The influence of waves on the transfer processes through the interface has been demonstrated. The mechanisms of heat and mass transfer enhancement in wave films have been analyzed.

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PREFACE

Beginning with the monograph of Hewitt and Taylor (1970), about a dozen books dedicated to liquid film flows have been published around the world in the last quarter century. Many of them were issued in the USSR: Vorontsov, Tananayko (1972), Gimbutis (1988), Kholpanov, Shkadov (1990) etc. Hydrodynamics and the processes of transfer in films constitute a rather small part of the field of mechanics. Nevertheless, the interest in moving films is rather great due to the distinguishing properties of the films and their broad application in technics. The strong influence of both viscosity and surface forces is a peculiarity of thin films. The interaction of inertial, viscous and capillary forces results in flow instability and the emergence of nonlinear waves that strongly influence the heat-mass transfer. The description of nonlinear wave formation and its influence on the transfer processes is one of the basic problems of liquid film mechanics. It should be noted that due to the variety of the observed physical phenomena, the results of thin film flow study are of great interest not only for liquid film mechanics, but also for more general scientific disciplines such as wave theory, multiphase media mechanics, and heat-mass transfer theory.

The principal goal of this book is the generalization of existing knowledge on the wave motion of gravitational thin liquid films and on the processes of transfer in the wave regimes of a flow. This is the only book that is expressly dedicated to wave phenomena in films. The greater part of the material is based on the works of the authors of the present publication which were carried out during 1970-1990.

NOMENCLATURE

a	- thermal diffusivity, m^2/s	(see, 13.3)
	- dimensionless amplitude of perturbation	(see, 6.5, 13.1.2, 13.5)
	- characteristic length scale for standing waves, m	(see, 10.2)
	- constant, 1/s	(see, 14)
$a = h_{max} - h_{min}$	- wave amplitude, m	
a_0	- initial dimensionless amplitude of perturbation	
a_∞	- asymptotic value of dimensionless amplitude	
a_{max}	- maximum value of dimensionless amplitude	
$a' = h' - h_0$	- amplitude of localized perturbations, m	(see, 9)
$a' = h_{max} - h_{res}$	- amplitude, m	(see, 8)
a'^*	- dimensionless amplitude of soliton	
$\tilde{a}_1$	- dimensionless amplitude of the first harmonic	
$\tilde{a}_m = \frac{h_{max} - h_{min}}{h_{max} + h_{min}}$	- amplitude	
a_w	- coefficient of wave thermal diffusivity, m^2/s	
a_t	- coefficient of turbulent thermal diffusivity, m^2/s	
A	- area of phase velocity profile, m^2/s	(see, 6.2; 6.4)

	- amplitude of cross velocity perturbation, m/s	(see, 6.6)
	- intermediate expression	(see, 6.8.4; 6.9)
	- integration constant	(see, 6.11)
$A = h_{\max}$	- amplitude, m	
$A = 3 \operatorname{ctg} \Theta / \mathrm{Re}$	- dimensionless parameter	(see, 6.11; 10.2)
$2A = h_{\max} - (h_{\min,1} + h_{\min,2}) / 2$	- amplitude, m	(see, 11)
$< A >$	- average amplitude of large waves, m	(see, 11)
$\overline{A} = \dfrac{h_{\max} - (h_{\min,1} + h_{\min,2})/2}{< h >}$	- dimensionless amplitude	
$\tilde{A} = (h_{\max} - h_{\min})/ < h >$	- dimensionless amplitude	
A_c	- integration constant, m^2/s^2	
ΔA	- distance between real and imaginary images of mark-particle on photographic film, m	
b	- interelectrode distance, m	(see, 3)
	- constant	(see, 13.3)
	- parameter, m^5/s	(see, 14)
$B = \mathrm{Re}^3 / W$	- dimensionless parameter	
B	- intermediate expression	(see, 6.8.4)
c	- phase velocity, m/s	
	- phase velocity related to u_0	(see, 6.8 - 6.12)
	- phase velocity related to $q / < h >$	(see, 13.1.2)
	- dimensionless phase velocity	(see, 6.5)
c_g	- group velocity, m/s	
	- group velocity related to u_0,	(see, 6.11)
c_m	- extreme value of phase velocity, m/s	
$c_{\max}$	- maximum value of phase velocity, m/s	
c_i	- imaginary part of dimensionless complex velocity	
c_r	- real part of dimensionless complex velocity	
c_x, c_z	- components of the vector of phase wave velocity	
c_0	- velocity of kinematic wave which is equal to $3u_0$, m/s	
	- dimensionless velocity of kinematic wave which is equal to 3	(see, 6.11)
	- velocity of gravitational wave on	

a shallow water which is equal to $\sqrt{gh_0}$, m/s (see, 6.3; 14)

c_1, c_2 - dimensionless velocities of inertial waves

$\tilde{c} = c\bar{h}/\bar{q}$ - dimensionless phase velocity

$c*$ - dimensionless velocity of soliton

$\bar{c} = c/u_0$ - dimensionless phase velocity

$\bar{c} = c/U$ - dimensionless phase velocity (see, 12)

$\bar{c}_g = c_g/u_0$ - dimensionless group velocity

C - capacitance, F (see, 3.1.5)
- concentration, mol/m^3 (see, 3.3.4)
- integration constant, m^2/s^2 (see, 6.1)
- velocity of shock wave, m/s (see, 6.4)
- concentration, kg/m^3
- concentration, kg/kg (see, 13.3)

C_j - intermediate coefficients, ($j = 2,...,9$)

$C_f = 2\tau_W/\rho U_0^2$ - shear stress coefficient

C_L - mean flow rate concentration at a distance L, kg/m^3 (see, 13.1)

C_P - specific heat, J/(kg·K)

C_S - concentration on a free surface, kg/m^3 (see, 13.1)

C_W - concentration near the wall, kg/m^3

C_0 - concentration within volume, mol/m^3 (see, 3.3.4)
- concentration within volume, kg/m^3

C_∞ - concentration far from the wall, kg/m^3

$\tilde{C}_{ij}$ - crosscorrelation function, m^2

$\mathrm{Co} = Q/l_1\nu$ - dimensionless parameter, Reynolds number analogue

d - electrode diameter, m (see, 3)
- cylinder diameter, m (see, 8.1)
- constant, (see, 13.3)
- layer thickness behind a jump, m (see, 14)

D - diffusion coefficient, m^2/s
- intermediate expression (see, 6.8.4)

E - intermediate expression

f - function (see, 1, 4, 13.1.2)
- frequency, Hz

f_i - frequency of feed current of the i-th sensor, Hz

Δf - difference in frequencies of currents feeding two different sensors, Hz

$\tilde{f}(h)$ - function of thickness probability density, 1/m

$F = (\mathrm{F}i/\sin\Theta)^{1/11}$ - modified film number

$\tilde{F}(h)$ - function of probability distribution

$F_S = F^{11/5}$ - modified film number

F_0 - initial distribution of phase velocity, m/s

$\mathrm{Fi} = \sigma^3/\rho^3 g\nu^4$ - film number (Kapitza number)

$\mathrm{Fi} = \sigma^3/\rho_1^3 g\nu_1^4$ - film number for a "liquid-liquid" system

$\mathrm{Fo} = 2L/3h_0 Pe_D$ - Fourier number (see, 13.2)

$\mathrm{F}r = u_0^2/gh_0\cos\Theta$ - Froude number

g - free fall acceleration, m/s^2

g_i - projection of gravity acceleration onto the axis x_i, m/s^2

G_0 - function in the solution of Burgers equation, m^2/s

$G = g\bar{h}^3\sin\Theta/\bar{q}\nu$ - Galilei number determined by the averaged values

G - irrigation density, kg/(m·s) (see, 13.3)

$\mathrm{Ga} = gh_0^3\sin\Theta/\nu^2 = 3\,\mathrm{Re}$ - Galilei number

$\mathrm{Ga}_L = gL^3\sin\Theta/\nu^2$ - Galilei number

h - thickness of liquid film, m
- dimensionless thickness related to h_0 (see, 6.8-6.12)
- film thickness related to $< h >$ (see, 13.1.2)

h_i - initial thickness of film, m

h_0 - film thickness by Nusselt, m
- unperturbed thickness, m
- film thickness by Nusselt related to $< h >$ (see, 13.1.2)

$h_{\max}$ - maximum thickness, m

$h_{\min}$ - minimum thickness, m

h_{00} - calculated thickness (by Nusselt) on the cone at $x = 0$, m (see, 5.4.2)
- calculated thickness (by Nusselt) on the cylinder and sphere at $\Theta = \frac{\pi}{2}$, m (see, 5.4.3-5.4.5)
- calculated thickness (by Nusselt) in the absence of shear stress, m (see, 12)

]$< h >$ - average thickness, m

$\bar{h}$ - thickness averaged over the wave length, m

$\Delta\bar{h}$ - deviation of average thickness from unperturbed value, m

h' - thickness of perturbed layer ("steps" or solitary perturbation), m
h^+ - dimensionless thickness
h_+ - thickness of radial film at $r = r_+$, m
$\tilde{h} = h/\bar{h}$ - dimensionless thickness
$H = \dfrac{h - h_0}{h_0}$ - dimensionless perturbation of film thickness
$H = h / h_0$ - dimensionless film thickness (see, 5.3)
$H = h / l_1$ - dimensionless film thickness (see, 5.4.1)
$H = h / h_{00}$ - dimensionless film thickness (see, 5.4.2 - 5.4.5)
$H_i = h_i / h_0$ - dimensionless initial thickness (see, 5.3)
$H_i = h_i / l_1$ of a film (see, 5.4.1)
$H_i = h_i / h_{00}$ (see, 5.4.2 - 5.4.5)
$H_0(\xi)$ - stationary periodic solution
i - number of primary dimensionalities (see, 1)
- number of pulses in a train (see, 3)
- imaginary unit
I - electric current, A
I_d - diffusion current, A
j - density of mass flux, kg/(m^2·s)
$j = \left(\dfrac{\partial \Theta}{\partial Y}\right)_{Y=0}$ - dimensionless density of mass flux (see, 13.1.2)
j_0 - unperturbed value of mass flux density
J, J_0 - intensity of passed and incident radiation, W/m^2
$k = 2\pi / \lambda$ - wave number, m^{-1} (see, 6.1; 6.3; 6.6; 6.7)
$k = 2\pi h_0 / \lambda$ - dimensionless wave number, modulus of wave vector (see, 6.9)
k - dimensionless x-component of the wave number (see, 6.5)
$\vec{k}$ - wave vector, m^{-1}
k_i - imaginary part of dimensionless complex wave number
$k_m = 2\pi / \lambda_m$ - extreme value of the wave number, 1/m (see, 6.1)
- wave number of maximum growth waves, 1/m
k_m - wave number of maximum growth waves related to h_0^{-1} (see, 6.8)
$k_{\min}$ - minimum value of the wave number

k_N - wave number of neutral perturbations, 1/m (see, 6.6)
- dimensionless wave number of neutral perturbations

k_r - real part of dimensionless complex of wave number

k_S - dimensionless wave number

k_x, k_z - components of wave vector

$k_{x,N}$ - x-component of the wave vector of neutral perturbations

k_1, k_2 - wave numbers of neutral perturbations, 1/m

$\tilde{k} = 2\pi < h > /\lambda$ - wave number measured experimentally

$\tilde{k}_{cr}$ - critical wave number measured experimentally

$K = \frac{q}{L} \ln \frac{C_S - C_0}{C_S - C_L}$ - mass transfer coefficient, m/s

K - proportionality factor (see, 3)
- curvature, m^{-1}

K_T - theoretical value of mass transfer coefficient, m/s

$\mathrm{Ka} = r_a |d| / C_P$ - modified Kutateladze criterion of phase transition

$l = (3\nu^2/g)^{1/3}$ - length scale, m

l_0 - longitudinal scale of wavelength order, m

$l_1 = (xh_0^3)^{1/4}$ - length scale, m

L - film path length, m

L_1 - linear operator

L_{in} - length of initial film region, m

L_{in}^T - length of thermal initial region, m

L^+ - dimensionless length

L_s - length of smooth region on the film, m

$\tilde{L} = L/h_0$ - dimensionless film length

$\mathrm{Lu} = a / D$ - Lewis number

m - maximum number of determining similarity criteria (see, 1)
- z-component of dimensionless wave number (see, 6.5)
- dimensionless specific flow rate in the z-direction (see, 6.12)

n - relative refractive index

$n = \frac{C_0 - C_L}{C_0}$ - coefficient (see, 13.1)

$\vec{n}$ - unit normal vector

n_i - i-th component of unit normal vector
N - magnification factor (see, 3.2.6)
- amplitude of interface perturbation, m
Nu - Nusselt number
$\mathrm{Nu}^* = \frac{\alpha h}{\lambda_T}$ - Nusselt number
$<\mathrm{Nu}^*> = \frac{<\alpha> h}{\lambda_T}$ - average Nusselt number
$\mathrm{Nu}_* = \frac{\alpha}{\lambda_T}\left(\frac{\nu^2}{g}\right)^{1/3}$ - modified Nusselt number
Nu_{is} - Nusselt number for isothermal absorption
p - pressure, Pa
- dimensionless pressure (or pressure perturbation) (see, 6.5)
- pressure perturbation, Pa or dimensionless (see, 6.8; 6.9)
- pressure related to $\rho g h_0$ (see 6.10 - 6.12)
- parameter (integer) (see, 8.3)
- dimensionless function (see, 13.1.2)
p_α - pressure perturbation in the α-th medium, Pa
$\bar{p}$ - unperturbed pressure, Pa or dimensionless
$p^{(i)}$ - i-th approximation for pressure ($i = 0, 1, ...$)
P - unperturbed dimensionless pressure
P_0 - atmospheric pressure, Pa
- unperturbed pressure at medium interface, Pa (see, 6.6 - 6.7)
$\mathrm{Pe} = q / a$ - Peclet number
$\mathrm{Pe}_D = q / D$ - diffusion Peclet number
$\mathrm{Pr} = \nu / a$ - Prandtl number
$\boldsymbol{P}$ - total pressure, Pa
$\boldsymbol{P}_\alpha$ - total pressure in the α-th medium, Pa
q - specific flow rate per unit of film width, m^2/s
- specific flow rate related to q_0 (see, 6.10 - 6.12)
q_0 - specific flow rate in a smooth laminar film, m^2/s
$\bar{q}$ - specific flow rate average with respect to wavelength
$<q>$ - mean flow rate, m^2/s

q_T	- density of heat flux, W/m^2	
q_{TS}	- density of heat flux on a free surface, W/m^2	
q_{TW}	- density of heat flux at the wall, W/m^2	
Q	- volumetric liquid flow rate, m^3/s	
	- dimensionless perturbation of specific flow rate related to q_0	(see, 6.11, 6.12)
	- parameter	(see, 8.3)
r	- radius-vector modulus, m	(see, 6.12)
	- parameter (integer)	(see, 8.3)
	- radial coordinate, m	
$\vec{r}$	- radius-vector, m	
r_a	- heat of absorption, J/kg	
r_0	- jet radius near the wall, m	
r_1	- jump radius, m	
r_+	- coordinate of the point, where $\delta = h$, m	
$\bar{r}$	- dimensionless radial coordinate	
$\bar{r}_1$	- dimensionless jump radius	
R	- curvature radius, m	
	- maximum radius of cone, m	(see, 5.4.2)
	- radius of cylindrical or spherical surface, m	(see, 5.4.3 - 5.4.5)

$\tilde{R} = R/h_{00}$ - dimensionless radius

$\mathrm{Re} = q / \nu = h_0 u_0 / \nu$ - Reynolds number

$\mathrm{Re} = Q / 2\pi R\nu$ - film Reynolds number at convergent cone and sphere

$\mathrm{Re} = A / 2\nu$ - effective Re number for the Burgers equation

$\mathrm{Re} = h_0 U / \nu_1$ - Re number for a "liquid-liquid" system

Re_{cr} - critical Re number of transition to turbulent regime

Re'_{cr} - critical Re number according to linear theory

$\mathrm{Re}_H = 4q / \nu$ - Reynolds number determined by hydraulic film diameter

$\mathrm{Re}_r = Q / \nu r$ - local Re number

Re_{res} - Reynolds number determined by the thickness of residual layer

Re_W - critical Reynolds number of wave formation

$\mathrm{Re}_x = xU / \nu$ - Reynolds number

$\tilde{\mathrm{Re}} = \bar{q}/\nu$ - Reynolds number

Re_* - critical Re number of standing wave formation

Re' - Reynolds number for a step, solitary perturbation

s	- area, m^2	
$S=\sqrt{3\text{ctg}\,\Theta/\text{Re}}$	- dimensionless velocity of gravitational waves	(see, 6.11)
S	- dimensionless parameter	(see, 10.2)
S^*	- critical value of parameter S	
$\tilde{S}\equiv\tilde{S}_{ii}$	- spectral density normalized for the second central momentum	
$\tilde{S}_{ij}$	- spectral density of thickness pulsations, m^2/Hz	
$\text{Sc}=\nu/D$	- Schmidt number	
Sc_t	- turbulent Schmidt number	
$\text{Sh}=\beta L/D$	- Sherwood number	
Sh_0	- theoretical value of Sherwood number	
$\text{Sh}^L=Kh_0/D$	- Sherwood number	
Sh_0^L	- theoretical value of Sherwood number	
Sh_{is}	- Sherwood number for isothermal absorption	
$\text{Sh}_r=\beta r/D$	- Sherwood number	
$\text{Sh}_x=-\frac{x}{C_W-C_0}\left(\frac{\partial C}{\partial y}\right)_{y=0}$	- Sherwood number	
$<\text{Sh}^*>=<\beta>h/D$	- average Sherwood number	
t	- temperature, °C	(see, 13.1.1)
	- time, s	
	- dimensionless time	(see, 6.5, 6.8 - 6.12, 12, 13.1.2)
Δt	- time interval, s	
t_1	- time, s	
$\tilde{t}=tu_0/h_0$	- dimensionless time	
T	- wave period, s	(see, 13.1)
	- absolute temperature, K	(see, 13.3)
T_0	- initial temperature, K	
T_W	- temperature at the wall, K	
T_f	- mean mass temperature, K	
T_S	- temperature near the free surface	
$\vec{T}$	- unit tangential vector	
T_i	- the i-th component of unit tangential vector	
u	- longitudinal velocity component, m/s	
	- longitudinal velocity related to u_0	(see, 6.10 - 6.12)

- perturbation of longitudinal velocity, m/s or dimensionless (see, 6.9)
- perturbation of longitudinal velocity (see, 6.5)

u_{max} - maximum velocity, m/s

u_{res} - average velocity of residual layer, m/s

$u_0 = gh_0^2 / 3\nu$ - average velocity of laminar film by Nusselt, m/s

u_0 - mean flow rate velocity, m/s (see, 14)

u_i - the i-th component of velocity vector, m/s (see, 4, 6.1)
- dimensionless i-th component (or perturbation) of velocity (see, 6.5)

u_1, u_2, u_3 - dimensionless velocities in a film, the boundary layer of external medium, outside the boundary layer, respectively (see, 12)

$u^{(i)}$ - the i-th approximation

$\overline{u}$ - unperturbed longitudinal velocity, m/s or dimensionless

u_α - perturbation of longitudinal velosity in the α-th medium, m/s (see, 6.6, 6.7)

U - velocity at the film surface, m/s
- velocity at the surface related to $q / \langle h \rangle$ (see, 13.1.2)
- velocity at the surface related to u_0 (see, 6.10 - 6.11)
- velocity outside the boundary layer (see, 13.2)
- dimensionless unperturbed longitudinal velocity component (see, 6.5)

$U_0 = gh_0^2 / 2\nu$ - surface velocity of laminar vertical film by Nusselt, m/s

U_0 - jet velocity in the minimum cross-section, m/s

U_i - unperturbed dimensionless i-th velocity component (see, 6.4)

U_α - part of longitudinal velocity perturbation depending on y in the α-th medium, m/s (see, 6.6, 6.7)

U_∞ - unperturbed velocity of moving medium, m/s

U_∞^{cr} - critical value of unperturbed velocity, m/s

$\langle U \rangle$ - average surface velocity, m/s

v - cross velocity component, m/s
- cross velocity related to εu_0 (see, 6.9 - 6.12)

v_α - perturbation of cross velocity in the α-th medium, m/s

$v^{(i)}$ - the i-th approximation

V	- potential difference, V	
V_α	- part of cross velocity perturbation depending on y in the α-th medium, m/s	
w	- z-component of velocity, m/s	
	- z-component of velocity related to u_0	(see, 6.9, 6.12)
$w^{(i)}$	- the i-th approximation	
$W = \sigma/\rho g h_0^2 \sin\Theta$	- Weber number	
$We = \sigma/\rho h_0 u_0^2$	- Weber number	
$We = \sigma/h_0 U^2 \rho_1$	- Weber number for a "liquid-liquid" system	(see, 12)
$\tilde{W} = \sigma\bar{h}/3\rho\bar{q}\nu$	- Weber number determined by average values	
x	- longitudinal coordinate, m	
	- longitudinal coordinate related to h_0	(see, 6.8 - 6.12)
	- longitudinal coordinate related to l_0	(see, 12)
	- longitudinal coordinate related to λ	(see, 13.12)
x_i	- coordinate of mark-particle at the i-th flash, m	(see, 3.2.6)
	- coordinate of film formation onset, m	(see, 5.4)
	- Cartesian coordinate, i = 1, 2, 3, m	(see, 6.1)
	- dimensionless Cartesian coordinate	(see, 6.5)
$x_1 = \int_0^1 \frac{U d\xi}{c-U}$	- characteristic distance in absorption problems	(see, 13.1.2)
x_n	- dimensionless coordinate of maximum points of augmentation factor (n = 1, 2,...)	(see, 13.1.2)
x_l, x_w, x_t	- lengths of regions of laminar, wave, turbulent flow regimes, m	(see, 13.5)
Δx	- width of shock wave front, m	
$\bar{x} = x / a$	- dimensionless coordinate for standing waves	
$\tilde{x} = x / h_0$	- dimensionless longitudinal coordinate	(see, 6.10.2)
X	- point coordinate at the x-axis, m	(see, 6.12, 10.2)
$X = x / h_0$	- dimensionless coordinate	(see, 5.3)
$X = x / l_1$	- dimensionless coordinate	(see, 5.4.1)
$X = x / L$	- dimensionless coordinate	(see, 5.4.2)
y	- cross coordinate, m	
	- distance from the wall, m	
	- dimensionless cross coordinate	(see, 6.5)
	- dimensionless cross coordinate related to h_0	(see, 6.8 - 6.12, 12)

y_c - cross dimensionless coordinate of critical layer

y_i - cross coordinate of mark-particle at the i-th flash, m

$\bar{y} = y / a$ - dimensionless coordinate for standing waves

$\bar{y}_0$ - dimensionless characteristics of crest shape of standing waves

Y - cross coordinate related to $< h >$ (see, 13.1.2)
- part of potential φ depending on y, m^2/s
- integration constant, m^2/s

z - number of independent dimensional constants (see, 1)
- coordinate, m
- dimensionless coordinate related to l_0 (see, 6.9, 6.12)
- coordinate in a cylindrical system of coordinates, m (see, 14)

$\tilde{z} = \dfrac{z}{h_0}$ - dimensionless coordinate

Z - point coordinate at the z-axis, m

α - heat transfer coefficient, $W/(m^2 \cdot K)$
- coefficient characterizing the velocity profile (see, 4, 6.10, 6.11)
- parameter (see, 10.2)

$\alpha = -\lambda_T \left(\dfrac{\partial T}{\partial y}\right)_{y=0} \Big/ (T_W - T_f)$ - heat transfer coefficient, $W/(m^2 \cdot K)$ (see, 13.4)

$\alpha = q_T / (T_W - T_S)$ - heat transfer coefficient, $W/(m^2 \cdot K)$ (see, 13.5)

$< \alpha >$ - average heat transfer coefficient, $W/(m^2 \cdot K)$

$\bar{\alpha}$ - heat transfer coefficient averaged over wavelength, $W/(m^2 \cdot K)$

α_0 - heat transfer in the absence of waves, $W/(m^2 \cdot K)$

α_l, α_w, α_t - average coefficient of heat transfer in the regions of laminar, wave and turbulent flow regimes, $W/(m^2 \cdot K)$

(-α) - spatial increment related to h_0^{-1} (see, 6.11, 7)

β - coefficient characterizing the velocity profile (see, 4, 6.10)
- coefficient, m^3/s^2 (see, 6.3)

	- complex increment, 1/s	(see, 6.6)
	- time increment related to u_0 / h_0	(see, 6.11)
	- mass transfer coefficient	
$\beta = j / (C_0 - C_S)$	- mass transfer coefficient, m/s	(see, 13.1)
β^+	- dimensionless mass transfer coefficient	
γ	- specific electric conductivity, S/m	(see, 3)
	- coefficient characterizing the velocity profile	
	- coefficient, m^3/s	(see, 6.3)
	- modulus of dimensionless wave number	(see, 6.5)
	- dimensionless parameter	(see, 13.12)
$\gamma = c_g / c$	- group to phase velocity ratio	(see, 10.2)
Γ	- electric conduction, S	(see, 3)
δ_d	- thickness of diffusive layer, m	
	- thickness of diffusive layer related to $< h >$	(see, 13.1.2)
δ_T	- thickness of thermal layer, m	
δ_{ij}	- Kroneker symbol	
$\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$	- Laplacian, $1/m^2$	(see, 4)
Δ	- "supercritical state" parameter,	(see, 6.11)
	- thickness of boundary layer, m	(see, 12)
$\delta(x)$	- delta-function, 1/m	(see, 6.4)
δ	- constant	(see, 6.5)
	- scale of film thickness perturbation	(see, 6.8 - 6.11)
	- dimensionless thickness of boundary layer	(see, 12)
	- thickness of boundary layer, m	
δ_d^0	- unperturbed thickness of diffusive layer	
δ_d'	- pulsation amplitude of diffusive layer thickness	
$\varepsilon = h_0 / l_0$	- long-wave parameter	
$\varepsilon = < h > / \lambda$	- long-wave parameter	(see, 13.1.2)
ε	- relative dielectric permeability	(see, 3)
$\varepsilon_0 = 8.854 \cdot 10^{-12}$	- electric constant, F/m	
$\zeta = x / t$	- self-similar variable, m/s	
η	- perturbation of layer thickness, m	(see, 6.1, 6.3)
	- boundary deviation from unperturbed state, m	(see, 6.6, 6.7)
	- self-similar coordinate	(see, 14)
$\eta = y / h$	- self-similar coordinate	(see, 4)
$\eta = Y / \delta_d$	- self-similar coordinate	(see, 13.1.2)

$\eta = y\left(\frac{gh_0}{q\nu Dx}\right)^{1/3}$ - self-similar coordinate (see, 13.2)
η - amplitude of layer thickness perturbation, m
$\upsilon = DL/h^2U$ - contact time
Θ - angle of film flow inclination to horizon, rad
$\Theta = \frac{C - C_S}{C_0 - C_S}$ - dimensionless concentration (see, 13.1.2)
Θ_i - initial angle of film flow, rad
κ - linear absorption coefficient, 1/m
λ - wavelength, m
λ_m - extreme value of wavelength, m
λ_T - heat conduction coefficient, W/(m·K)
Λ - length of a smooth region between waves, m
μ - dynamic viscosity, Pa·s
- ratio of dynamic viscosities (see, 12)
μ_1, μ_2 - dynamic viscosity in a film and external medium, respectively, Pa·s
$\tilde{\mu}_i$ - central moment
ν - kinematic viscosity, m^2/s
- coefficient in the Burgers equation, m^2/s (see, 6.4)
- ratio of kinematic viscosities (see, 12)
ν_1, ν_2 - kinematic viscosity of the first and second media, m^2/s
ξ - independent variable, m (see, 6.4)
$\xi = kx + mz - \omega t$ - dimensionless "travelling" coordinate (see, 6.5)
$\xi = x - ct$ - dimensionless "travelling" coordinate (see 6.11, 8, 13.11)
ξ_1 - independent variable
Π_α - part of pressure perturbation depending on y in the α-th medium, N/m^2
π - polynomial, $1/m^2$
ρ - density, kg/m^3
- density ratio (see, 12)
ρ_α - density of the α-th medium, kg/m^3
σ - surface tension, kg/s^2
- dispersion parameter (see, 6.4)
σ_{ij} - stress tensor, N/m^2
σ_A - mean root square deviation of large wave amplitude, m
τ - time interval, s (see, 11)
$\tau = \tau_S h_0 / \mu_1 U$ - dimensionless shear stress

at interface (see, 12)

$\tau = \int_0^1 \frac{d\xi}{c-U}$ - dimensionless drift time of liquid particle along the surface (see, 13.1.2)

$\vec{\tau}$ - unit tangential vector

τ_i - the i-th component of unit tangential vector

τ_S - shear stress at interface, N/m^2

τ_W - shear stress at the solid wall, N/m^2

$< \tau_W >$ - mean shear stress at the wall, N/m^2

$\sqrt{\overline{\tau_W'^2}}$ - RMS of shear stress pulsations at the wall, N/m^2

φ - velocity potential, m^2/s (see, 6.1)
- function in the Cole-Hopf transformation (see, 6.4)
- part of cross velocity perturbation depending on y (see, 6.5)
- angle of wave propagation relatively to the x-axis, rad (see, 6.12, 10.2)
- perturbation of periodic solution, (see, 8.3)
- phase (see, 13.1.2, 13.5)

$\varphi = \tilde{h} - 1$ - dimensionless thickness deviation from the average value (see, 6.10.2)

φ_i - part of stream function perturbation depending on y in the i-th medium

φ_0 - characteristic angle of wave crest shape, degree

$\Phi = 9.648 \cdot 10^4$ - Faraday' constant, C/mol
- dimensionless function (see, 6.11)

$\Phi(\xi)$ - periodic function

$\Phi_0(\xi)$ - initial distribution of function $\varphi(x, t)$

χ - independent variable, m (see, 6.4)

$\chi = \beta / \alpha^2$ - coefficient characterizing the velocity profile (see, 6.11.1)

ψ - perturbation of stream function, m^2/s or dimensionless (see, 6.8)
- part of pressure perturbation depending on y (see, 6.5)

$\overline{\Psi}$ - unperturbed value of stream function, m^2/s or dimensionless

$\psi^{(i)}$ - the i-th approximation for the stream function

ψ_i - perturbation of dimensionless stream function in the i-th medium

Ψ	- stream function, m^2/s	
	- dimensionless stream function	(see, 13.2)
ω	- angular frequency, rad/s	
	- dimensionless frequency	(see, 6.5)
	- complex frequency, rad/s	(see, 6.7)
	- complex frequency related to u_0 / h_0	(see, 6.8, 6.9)
ω_i	- imaginary part of dimensionless complex frequency	
ω_r	- real part of dimensionless complex frequency	

1

INTRODUCTION

1.1. Basic Concepts

A film flow is defined as a liquid layer falling down at least one free boundary under the effect of gravity, shear stress etc. Liquid films have a number of peculiarities. They are, therefore, assigned to a separate class of flows. First of all one should note the small thickness (0.1 - 1 mm) of the films compared to the characteristic sizes which are usually encountered in nature and patterns of liquid flows. The typical range of Reynolds numbers is 1~ 10 , i.e. where the effect of viscosity forces is almost always essential. On the other hand, the presence of a free surface with comparable scales of the film thickness and capillary constant means a strong influence of surface perturbations on a film flow. For these reasons the mathematical description of the perturbed motion of a liquid film even in the simplest statement is extremely complicated. An essential simplification is, however, possible for long-wave perturbations when the boundary layer approximation seems rather appropriate.

Figure 1.1 illustrates the typical geometry for some types of film flows. The gravitational flow of a film over an inclined plane and the outer surface of a vertical tube has been studied most frequently though surfaces of any profile, including the rough ones, are encountered in practice. The cases of film falling down the moving bodies, in particular, vibrating and rotating ones, are the most complicated examples.

A combined flow of the liquid film and gas, i.e. two-phase (annular) flow, is frequently realized in engineering. An annular flow is one of the flow patterns of vapour-liquid mixture motion in a vapour generating channel. The relative motion of phases results in the appearance of additional shear and normal

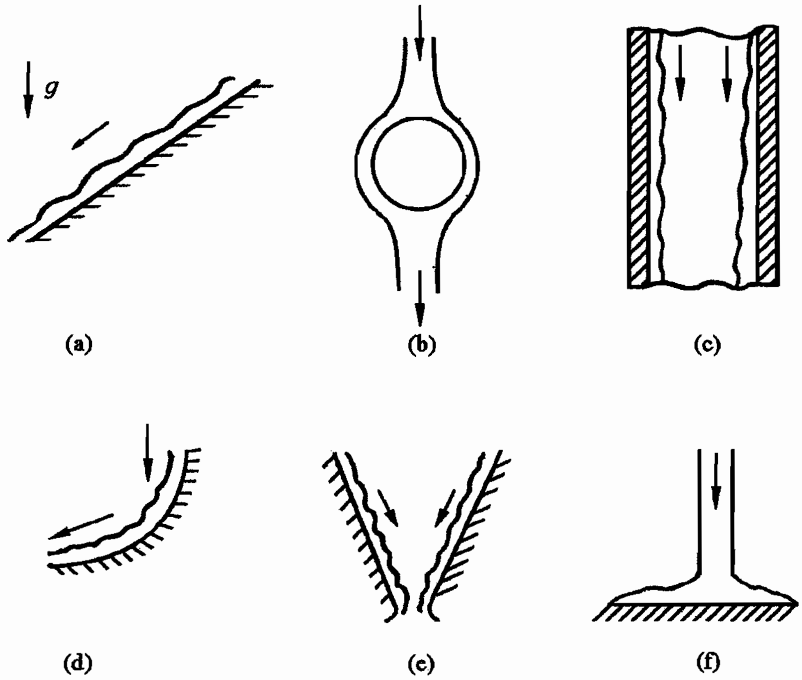

Figure 1.1. Geometry of film flows: (a) - film falling down an inclined surface; (b) - flow past a cylinder; (c) - film flow along the internal surface of a tube; (d) - falling down a curvilinear surface; (e) - flow along the internal surface of a cone; (f) - jet spreading along the surface

stresses at the interface and affects essentially the structure of interface. In this paper, however, primary attention will be given to the purely gravitational motion of films.

A spatial film which represents a continuous layer of the liquid with two free boundaries is the particular case of the films. In fact such film is a plane liquid jet, in which the viscous effects are negligible due to the absence of a solid surface.

1.2. Waves

The flow instability giving rise to the appearance of nonlinear surface waves even at the Reynolds numbers of the order of one is the characteristic feature of the films. Visual observations reveal a great variety of wave patterns from linear two-dimensional waves to strongly nonlinear three-dimensional soliton-like

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